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Disinfection of Filtered and Unfiltered Secondary Effluent in Two Ozone Contactors

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16. ABSTRACT
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DISINFECTION OF FILTERED AND UNFILTERED SECONDARY EFFLUENT IN TWO OZONE CONTACTORS

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The objective of this study was to evaluate the effect of filtration of secondary effluent on the mass transfer and disinfection efficiencies of two ozone contactors. The two contactors used in the comparison were a multicolumn bubble diffuser and a stirred tank reactor. The approach chosen was based on a type of statistical experimental design used in a previous contactor comparison. The design made it possible to compare the ozone transfer and coliform reduction efficiencies of the two contactors with respect to applied dose, while at the same time comparing filtered and unfiltered effluent. Results indicated that better mass transfer efficiency and, consequently, better coliform reduction efficiency occurred in the bubble diffuser, and the differences between contactors increased with dose. Mass transfer in both contactors was higher in unfiltered effluent than in filtered effluent. The most significant factors affecting the fecal coliform numbers in the treated secondary effluent were total chemical oxygen demand (COD) and absorbed ozone dose. Regression equations were developed to predict final coliform numbers as a function of COD and absorbed ozone dose.

Introduction

In 1976, the U.S. Environmental Protection Agency initiated an in-house research study comparing the ozone transfer and microorganism reduction efficiencies of various generic-type gas–liquid contactors. At that time several wastewater treatment plants using ozone for disinfection were in various stages of design or construction. The types of ozone contactors being designed for those plants at that time varied widely. For example, at Woodlands, Texas, a packed column was being built; at the Upper Thompson Sanitation District (Estes Park, Colorado), a bubble diffuser; at Mahoning County Sanitation District (Meander Creek, Ohio), a pressure injector; at Springfield, Missouri, a slow speed turbine; at Indiantown, Florida, a high speed turbine combined with ultrasonics. It was not known which type of contactor provided the best mass transfer and disinfection efficiency. Hence, the present study was undertaken to determine the answer and to provide some rational basis for arriving at a standard design guideline useful for all municipal treatment plants choosing ozone for disinfection.

As the research study progressed, it became apparent that improved disinfection efficiency was achievable when the effluent was filtered prior to ozonation. It was not clear at the time that removing a portion of the suspended solids in secondary effluent would significantly affect disinfection efficiency with ozone. Evidence supporting this hypothesis was only suggestive. Ward *et al.* (1976) at Grandville, Michigan, found in a previous study that filtering the effluent prior to ozonation aided in achieving better coliform reductions. If this could be confirmed under rigorous experimental conditions, the reliability and economics of ozone disinfection of secondary effluent would be significantly affected. Hence, an in-depth evaluation of the effect of effluent filtration on the performance of two different ozone contactors was undertaken in late 1978. The contactors used in the evaluation were a bubble diffuser and a

stirred turbine reactor. In this paper, the results from that study will be presented, but no economic evaluation will be made.

Definitions of terms used in this report are given below.

1. Applied Ozone Dose (D):
$$D = Y_1(Q_G/Q_L), \quad (1)$$
where Y_1 = concentration of ozone in the carrier gas (mg O_3/l_{gas});
Q_G = carrier gas flow rate (l_{gas}/min);
Q_L = liquid flow rate (l_{gas}/min).
2. Transfer Efficiency (TE):
$$TE = 100(Y_1 - Y_2)/Y_1, \quad (2)$$
where Y_2 = concentration of ozone in the gas leaving the contactor (mg O_3/l_{gas}).
3. Absorbed Dose or Ozone Transfer (T):
$$T = D \times \text{fraction transferred}$$
$$= Y_1(Q_G/Q_L)(Y_1 - Y_2)/Y_1$$
$$= Q_G/Q_L(Y_1 - Y_2). \quad (3)$$

Materials and Methods

Sources of Secondary Effluent

Secondary effluent was obtained from three different sources: (1) the EPA pilot plant at the Robert A. Taft Laboratory (RATL), Cincinnati, Ohio; (2) the Muddy Creek Treatment Works (MCTW), Cincinnati, Ohio; and (3) the Fairfield, Ohio, Wastewater Treatment Plant (FWTP). All three were conventional activated sludge treatment plants receiving raw wastewater of municipal origin. A multimedia pressure filter (Baker Filtration Company, Model HRC-30D) was used to filter the test effluent prior to ozonation.

Effluent from the RATL pilot plant was split, either directly from the final clarifier or after the pressure filter, between the two contactors for parallel evaluation. When secondary effluent was obtained from the MCTW and FWTP plants, approximately 20 m^3 was collected in a tank truck on the day of an experimental run and transported to the RATL pilot facility. The effluent was pumped either directly to a contactor or first through the pressure filter. Since the effluent in this circumstance was serving as a batch source, there was no need to operate the contactors in parallel.

Ozone generation

Ozone was generated from air in a plate-type, corona discharge generator (Computerized Pollution Abatement Corporation Model OZ-180G). Gas from the generator was split into two lines, each having a rotameter and valve for flow control. These lines served as ozone feed to the contactors.

The carrier air was filtered (Pall Trinity Micro Corporation Model No. MCC1001SV160) and then dried to an average dew point of $-45\,°C$ (std. dev. = $\pm 1.5\,°C$) by an activated alumina dryer (Pall Trinity Micro Corporation 25 HA1). The dew point was measured daily in an Alnor Dew Pointer (Model 7300, Alnor Instrument Company, Niles, Illinois). Carrier air leaving the drying unit was filtered again (Pall Trinity Micro Corporation Model No. MCC1101EC12) prior to entering the ozonator.

Ozone contactors

Figure 1 is a schematic diagram of the three-stage bubble diffuser (BD) contactor. The BD consisted of three aluminum columns, each 3.7 m high, 300 mm in diameter, connected in series by PVC piping. The three columns were staggered vertically so that secondary effluent, which was pumped to the top of the first column, could flow by gravity to each of the two successive columns. The ozone enriched gas was injected through domed ceramic diffusers (Norton Chemical Process Products Division) located at the bottom of each column and connected in parallel to a common header pipe. Gas and liquid sample taps were located as shown in Fig. 1. Since the BD was operated as a system, treated effluent samples were collected at the sample tap of the last column only, while exhaust gas samples were collected after the exhaust gas from each column had been combined into a common line (see Fig. 1). Mean liquid residence time in the BD contactor, measured by a dye study, was 9.4 min at a liquid flow rate of 75 l/min and a gas flow rate of 40 l/min.

Figure 2 is a schematic diagram of the stirred turbine reactor (STR). The STR consisted of a stainless steel vessel measuring 500 mm in diameter and 630 mm deep. The vessel was enclosed by a stainless steel cover and sealed with a Teflon envelope gasket. The impellor assembly consisted of a shaft with two 4-blade impellors measuring 200 mm long. The lower impellor was situated 100 mm above the bottom of the vessel, and the upper impellor 300 mm above that. Three stainless steel baffles were fixed to the inner side of the vessel to aid in the mixing. Ozone-enriched air, entering the STR through a 13 mm tube, was injected tangentially to the wall of the vessel rather than directly under the bottom impellor blade to prevent aspiration of the gas down the secondary effluent pipeline. The gas exited the top of the chamber through a 25 mm pipe. Secondary effluent entered the top of the STR through a 50 mm tube and exited the bottom through a 100 mm pipe. The impellors were driven by a variable speed drive at 360 revolutions per minute (rpm). Contact time in the STR at a liquid flow rate of 50 l/min was 2.5 min.

Sampling

All effluent samples were grab samples and were analyzed for total and soluble chemical oxygen demand (TCOD and SCOD, respectively), total organic carbon (TOC), total suspended solids (TSS), and turbidity by *Standard Methods for the Examination of Water and Wastewater* (American Public Health Association, 1975).

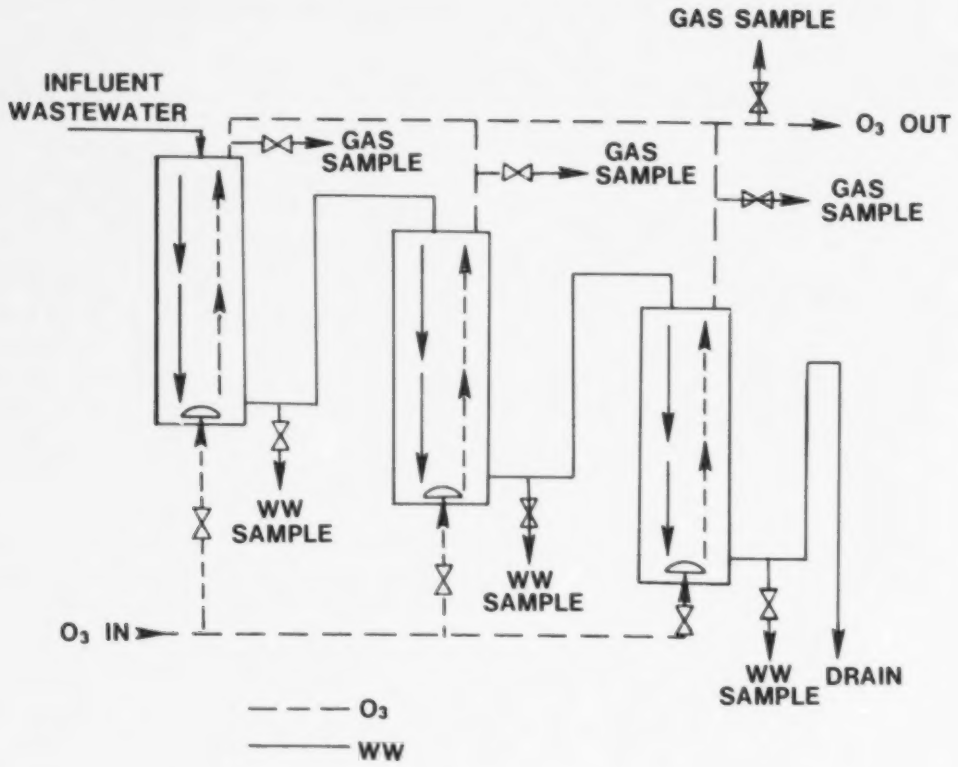

Fig. 1. Bubble diffuser ozone contactor.

Total Kjeldahl nitrogen (TKN), ammonium nitrogen (NH_4^+ – N), and nitrite–nitrogen (NO_2^- – N) were measured according to "Methods for Chemical Analysis of Wastes" (U.S. Environmental Protection Agency, 1975) and nitrate–nitrogen (NO_3^- – N) according to Kamphake, Hannah, and Cohen (1967).

Samples collected for bacteriological analysis were assayed for total and fecal coliforms by the standard membrane filtration (MF) method (American Public Health Association, 1975) using 0.45 μm GN-6 membrane filters (Gelman Instrument Company).

Experimental design

The approach chosen was based on a type of statistical experimental design used in a previous contactor comparison (Venosa *et al.*, 1979). The design used was a split plot design where the whole plot treatments were arranged in a partially balanced incomplete block design (Federer, 1975). It was set up by day (i.e., block) so that observations to be taken each day comprised an entire replicate run encompassing all levels of each factor. The factors were applied ozone dose (3 levels), contactor type (2 levels), and effluent treatment (filtered vs unfiltered). Using this type of design it was possible to compare the ozone transfer and coliform reduction efficiencies of two different ozone contactors with respect to applied dose while simultaneously evaluating the role of filtration on contactor performance. To minimize any trend in wastewater effluent quality in a given day, the design was balanced so that each dose level occurred the same number of times at each time of day. The first set of observations was taken in the morning, the second set around noon, and the final set in the afternoon. The sampling order on any given day was randomized. A total of 12 sampling days comprised one complete experiment. Both contactors were compared on filtered effluent three days and on unfiltered effluent three days, whereas on the other six days one contactor was tested on filtered effluent and the other on unfiltered effluent.

The split plot design discussed above was chosen for several reasons. It was expected that the greatest variation in effluent quality would be the day-to-day variation, whereas substantially lesser variation would occur within a day. Since the number of treatments being used was more than could be run in one day, it was necessary to block the treatments in some way. The split plot design allowed us to run every dose level each day so that differences in dose responses would not be affected by the expected large day-to-day variation in effluent quality. This allowed for a much greater precision in estimating dose effects and whole plot treatment-by-dose effects than would be the case if the day-to-day variation were pooled with the experimental error. Only the

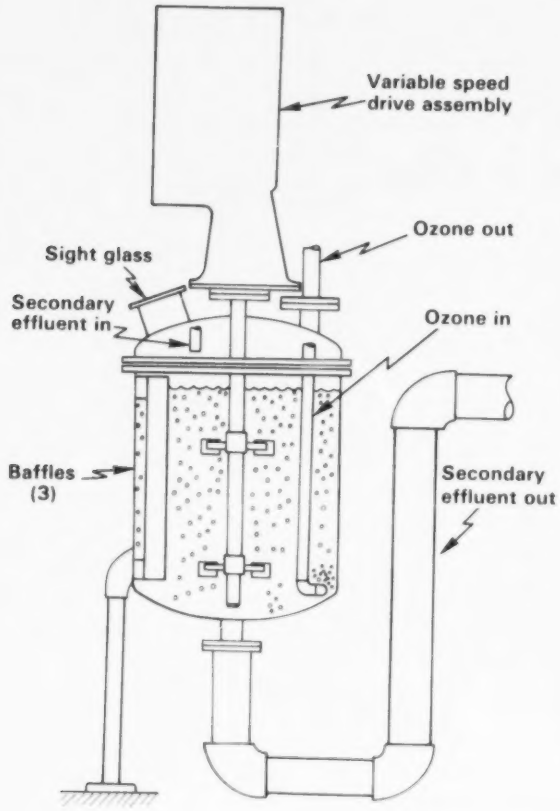

Fig. 2. Stirred tank reactor.

whole plot treatments had the day-to-day variation as their experimental error. The necessity of running the whole plots in partially balanced incomplete block design was due to physical restrictions that did not allow certain combinations of contactors and filtration to occur at the same time. There was the additional restriction that each contactor could only receive one type of effluent (filtered or unfiltered) in a given day rather than both types.

Two experiments were conducted. The three ozone dose levels chosen in the first experiment were achieved by holding the Y_1 constant and varying the Q_G/Q_L ratio. The second experiment was performed by varying the Y_1 and holding the Q_G/Q_L constant. The dependent variables forming the basis of comparison of the contactors and of filtered vs unfiltered effluent were total and fecal coliform log reduction [$\log_{10}(N_0/N_1)$ where N_0 = initial coliform number, and N_1 = final coliform number], transfer efficiency and absorbed ozone dose. Results were analyzed by analysis of variance (ANOVA) and multiple regression techniques. Data analyses were facilitated by an IBM 370 computer, using the Statistical Analysis System (SAS) General Linear Models (GLM) procedure and the *R* Square procedure (Barr *et al.*, 1976).

Results and Discussion

Optimization of the STR

Prior to start, attempts were made to optimize the transfer efficiency of the STR. There were three independent variables of interest: (1) impellor blade pitch, (2) rotation speed, and (3) liquid residence time. Two completely random factorial experiments were conducted to evaluate these factors.

In the first experiment the STR was operated at liquid flow rates of 25, 50, 75, and 100 l/min, corresponding to liquid residence times of 5.0, 2.5, 1.67, and 1.25 min, respectively. The applied ozone dose was held constant at 6.0 mg/l ($Q_G/Q_L = 0.6$, $Y_1 = 10$ mg/l). RATL secondary effluent served as the liquid source. The impellor blades were set at 90° to the horizontal, and the speed of rotation was varied between 150, 220, 290, and 360 rpm. Two replicate runs were conducted with the dependent variable being ozone transfer efficiency. Results were analyzed by analysis of variance. The second experiment was an exact repeat of the first experiment, except that the impellor blades were set 45° to the horizontal.

Results of both experiments are presented graphically in Fig. 3. Transfer efficiency in the STR increased substantially with impellor rotation speed (Fig. 3a) and decreased slightly with increasing Q_L (Fig. 3b). Better TE was consistently achieved with the impellors set at 90° to the horizontal. The analyses of variance of the two experiments are summarized in Tables 1 and 2.

In both cases the effects of flow rate and rpm on TE were highly significant ($p < 0.01$). The flow × rpm interactions were not significant, indicating that the differences in TE with rpm were consistent at each flow rate. As a result of these experiments, the following operating conditions were selected for the STR for all subsequent work: (1) impellors set at 90° to the horizontal; (2) rotation speed set at 360 rpm; and (3) Q_L set at 50 l/min. Although optimum TE in the STR occurred at $Q_L = 25$ l/min, a higher flow rate was chosen because the increased power requirements to operate the STR and the added capital cost of the STR at the lower flow rate did not justify operating under that condition.

Effect of increasing Q_G/Q_L at a constant Y_1

Using the split plot design discussed earlier, an experiment was conducted to evaluate the effect of increasing the applied ozone dose to each contactor by increasing the Q_G/Q_L ratio while maintaining a constant inlet ozone concentration (Y_1). The Y_1 chosen was 12 mg/l (approximately 1 wt.%), and the Q_G/Q_L ratios were 0.33, 0.83, and 1.33. These conditions resulted in applied dose levels of 4, 10, and 16 mg/l, respectively.

Effluent quality. In this experiment secondary effluent was obtained from the RATL pilot plant and the MCTW treatment plant. Table 3 summarizes the physical–chemical and bacteriological characteristics of

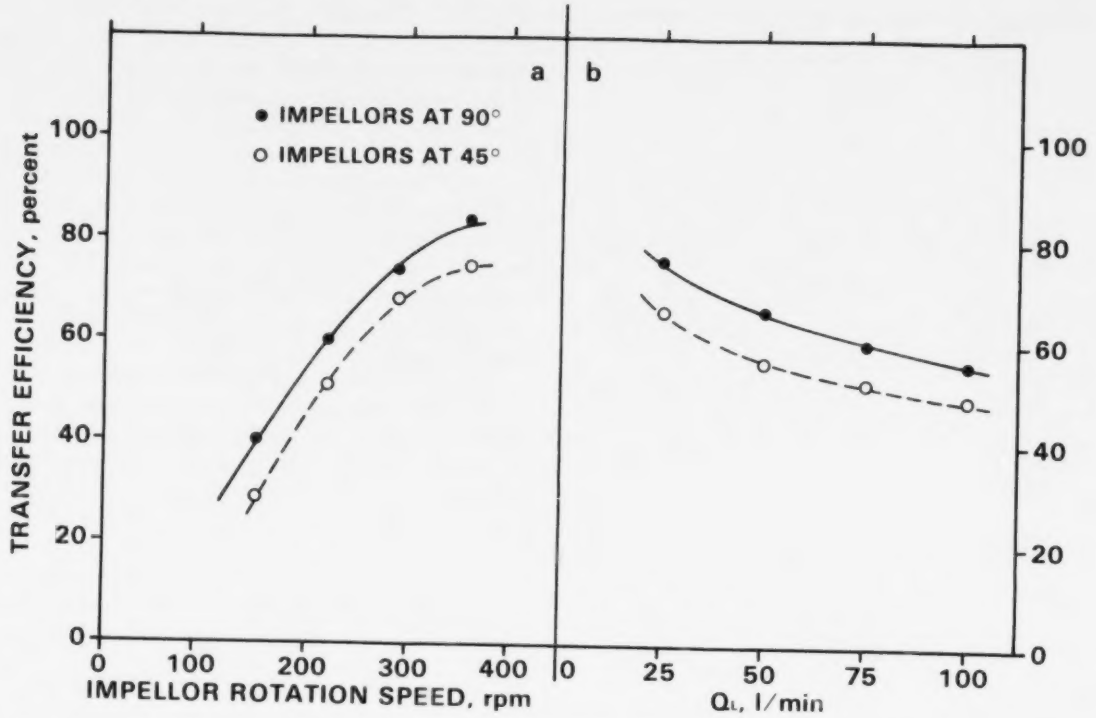

Fig. 3. Effect of impellor blade pitch on transfer efficiency of STR at various impellor rotation speeds (a) and liquid flow rates (b).

the effluents before and after filtration and before ozonation (data of both effluents combined). Quality was not typical of an average secondary effluent, as evidenced by the low suspended solids level. Note that filtration of the effluent did not substantially change the physical–chemical characteristics but did result in removal of almost one order of magnitude of total and fecal coliforms. The range in coliform numbers is typical of the expected range in secondary effluent.

Table 1. ANOVA for experiment with impellors set at 90°.

Source of variation	Degrees of freedom	Sum of squares	Mean square	*F*-value
Day	1	47.53	47.53	8.49
Flow	3	1852.34	617.45	110.30*
rpm	3	8542.84	2847.61	508.69*
Flow × rpm	9	169.28	18.81	3.36
Error	15	83.97	5.60	
Total	31			

*Significant at $p<0.01$.

Table 2. ANOVA for experiment with impellors set at 45°.

Source of Variation	Degrees of freedom	Sum of squares	Mean square	*F*-value
Day	1	18.00	18.00	0.76
Flow	3	1418.50	472.83	20.04*
rpm	3	10,182.75	3394.25	143.82*
Flow × rpm	9	178.25	19.81	0.84
Error	15	354.00	23.60	
Total	31			

*Significant at $p<0.01$.

Anova's. Table 4 summarizes the analyses of variance of all data from the first experiment with respect to each of the four dependent variables. Interpretation of the results is facilitated by first considering the interactions before studying the main effects.

The dose × contactor interaction was highly significant with respect to all dependent variables. These effects are graphically depicted in Fig. 4. The figure was constructed by averaging together the data from the filtered and unfiltered effluent and plotting the means for both contactors. The ozone transfer efficiency in the BD decreased less rapidly than in the STR (Fig. 4a). This signifies that at higher dose levels (i.e., higher Q_G/Q_L ratio) the BD was more capable of absorbing the added ozone than the STR, and indeed Fig. 4b demonstrates this clearly. The different rates of increase in mass transfer with increasing dose had a dramatic effect on microorganism reduction (Figs. 4c and 4d). Significantly higher total and fecal coliform log reductions (TCLR and FCLR, respectively) occurred in the BD than in the STR as the dose was increased.

The dose × filter interaction is shown graphically in Fig. 5. This figure was constructed by averaging together the data from both contactors and plotting the means for filtered and unfiltered effluents. The interaction was highly significant with respect to transfer

Table 3. Secondary effluent characteristics prior to ozonation (11/30/78 to 2/15/79) (RATL and MCTW effluents combined).

Parameter	Unfiltered mean (range)	Filtered mean (range)
TCOD, mg/l	42 (29–65)	32 (23–55)
SCOD, mg/l	35 (23–59)	31 (20–58)
TOC, mg/l	9.9 (5.9–20.6)	8.7 (5.9–18.2)
TSS, mg/l	6 (2–16)	4 (1–10)
TKN, mg/l	15.1 (7.1–22.7)	10.7 (3.3–21.7)
NH_4^+ –N, mg/l	6.3 (1.8–13.2)	6.1 (2.2–11.2)
NO_2^- –N, mg/l	0.4 (<0.1–2.6)	0.06 (<0.1–0.3)
NO_3^- –N, mg/l	0.3 (<0.1–0.8)	0.2 (<0.1–0.7)
Turbidity, JTU	4.1 (1.3–8.3)	2.1 (0.1–6.4)
Mn, mg/l	0.15 (0.04–0.38)	0.19 (0.04–0.38)
Fe, mg/l	0.24 (<0.01–0.67)	0.10 (0.01–0.34)
*p*H	(6.1–8.8)	(6.5–8.8)
Temperature, °C	15 (8–21)	15 (8–21)
$\log_{10}$TC/100 ml	5.92 (5.05–7.04)	4.88 (4.32–6.85)
$\log_{10}$FC/100 ml	4.93 (3.50–6.42)	4.06 (3.44–6.02)

efficiency (Fig. 5a) and absorbed ozone (Fig. 5b). This signifies that the rate of change in TE or T with increasing dose was different in filtered as compared with unfiltered effluent. However, the dose × filter interaction was not significant with respect to TCLR (Fig. 5c). This does not mean that there was no difference in TCLR between filtered and unfiltered effluent. It simply means that the *rates* of increase in TCLR for the two effluent treatments were the same. In other words, the two curves in Fig. 5c are essentially parallel. The $D \times F$ interaction for FCLR was significant (Fig. 5d), indicating the rates of increase in FCLR were different for filtered and unfiltered effluent. The cause of the interaction is evident by examining the highest dose level (Fig. 5d), where the mean FCLR's for the filtered and unfiltered effluent were essentially equal. At the other two dose levels a consistently higher FCLR was achieved in the filtered effluent.

The dose main effect (Table 4) was tested using the dose × block interaction as the error term. The dose effect was highly significant with respect to all four dependent variables. As dose was increased, transfer efficiency in both contactors decreased, the amount of ozone absorbed increased, and coliform reduction increased.

In the whole plot analysis (Table 4), the dose effect was eliminated from consideration by averaging the results over all dose levels and then examining the means for appropriate differences. The contactor × filter interactions are displayed graphically in Fig. 6. The means for filtered effluent were connected by straight lines to the means for unfiltered effluent merely to emphasize the contactor × filter interactions or lack thereof, and not to show a continuity between the two treatments. The interaction was significant with respect to transfer efficiency and absorbed dose (Figs. 6a and 6b). However, the results were equivocal since the significance level was only 0.05 (see Table 4). In other words, there is some evidence to indicate that mass transfer differences between contactors were not the same in filtered compared with unfiltered effluent. It appears that the bubble diffuser contactor might have

Table 4. ANOVA for all data from first experiment (constant Y_1, varying Q_G/Q_L).

Source of variation	Degrees of freedom	Transfer Efficiency Mean square	Transfer Efficiency *F*	Absorbed Dose Mean square	Absorbed Dose *F*	TCLR Mean square	TCLR *F*	FCLR Mean square	FCLR *F*
Whole plot analysis									
Blocks (days) (B)	11	158.88	13.75**	2.38	10.79**	1.94	2.08	2.81	4.81*
Contactors (C)	1	496.12	42.93**	18.71	84.83**	8.56	9.19*	4.63	7.91*
Filter (F)	1	23.36	2.02	0.59	2.66	6.45	6.93*	5.00	8.55*
$C \times F$	1	100.00	8.65*	1.32	6.00*	1.23	1.32	0.69	1.17
Error a	9	11.56		0.22		0.93		0.58	
Split plot analysis									
Dose (D)	2	5626.62	247.70**	228.63	322.60**	18.73	49.88**	17.39	34.97**
$D \times C$	2	837.79	94.04**	12.28	125.24**	2.17	9.74**	1.51	16.97**
$D \times F$	2	67.35	7.56**	1.01	10.31**	0.12	0.54	0.70	3.95*
$D \times C \times F$	2	0.85	0.10	0.11	1.12	0.54	2.40	0.31	3.52
$B \times D$	22	22.72	2.55*	0.71	7.23**	0.38	1.68	0.50	5.60**
$D \times$ error a	18	8.91		0.098		0.22		0.089	
Total	71								

*Significant at the $p < 0.05$ level.
**Significant at the $p < 0.01$ level.

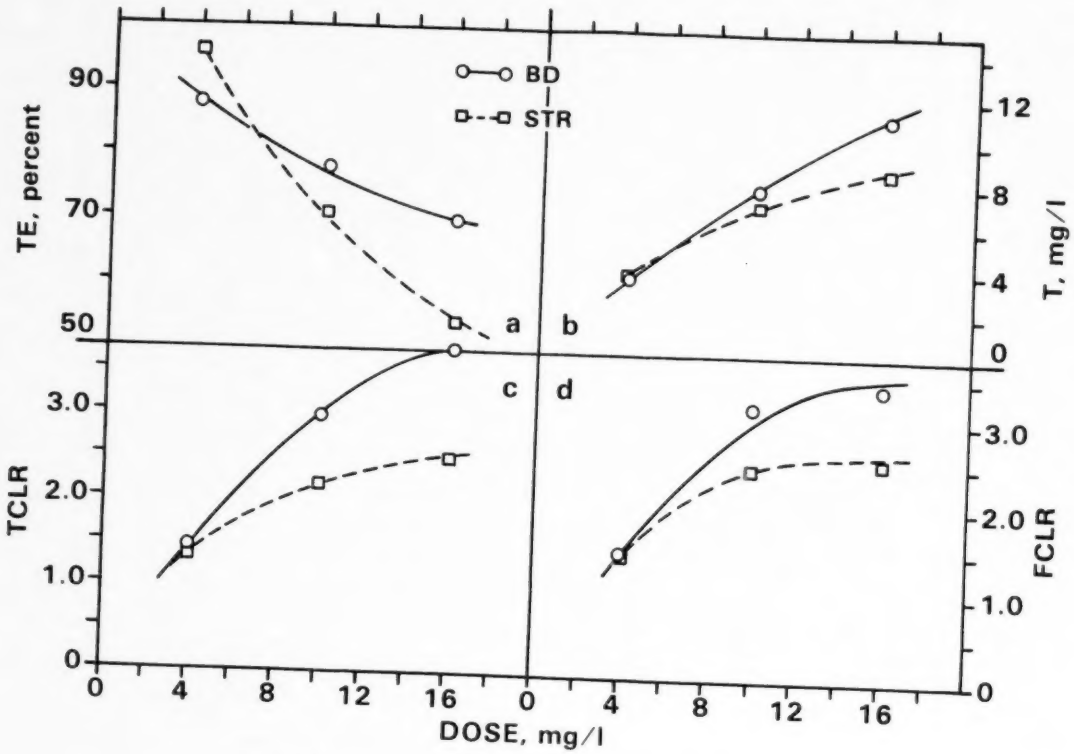

Fig. 4. Dose×contactor interaction (constant Y_1, varying Q_C/Q_I ratios).

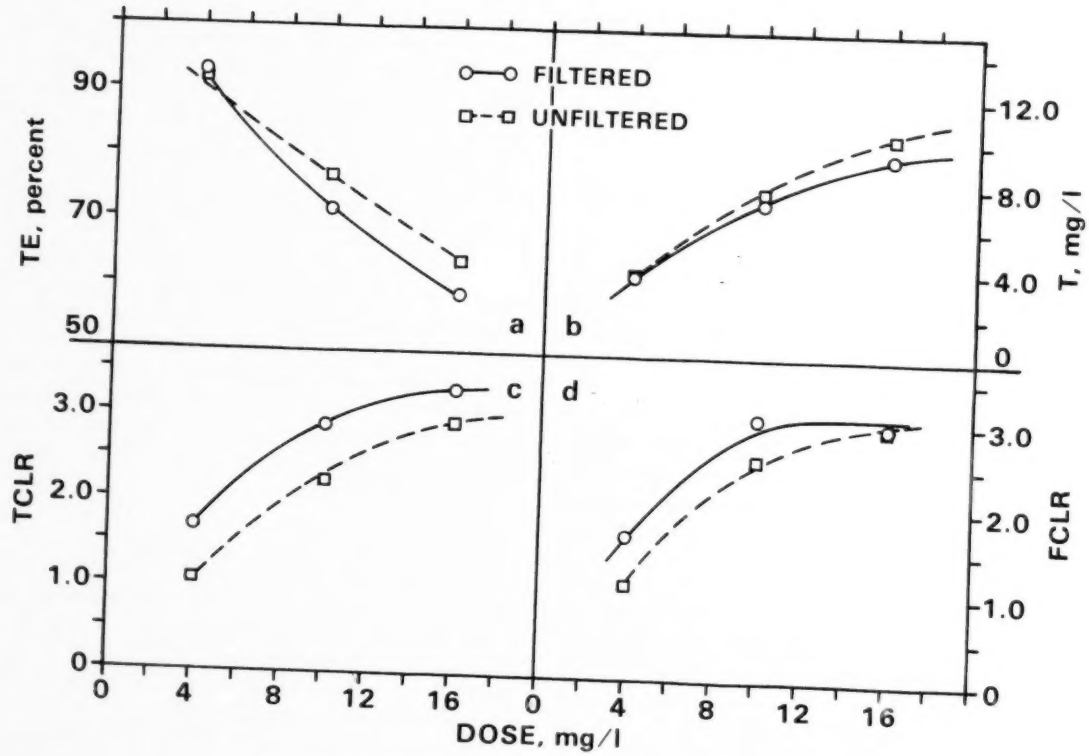

Fig. 5. Dose×filter interaction (constant Y_1, varying Q_C/Q_I ratios).

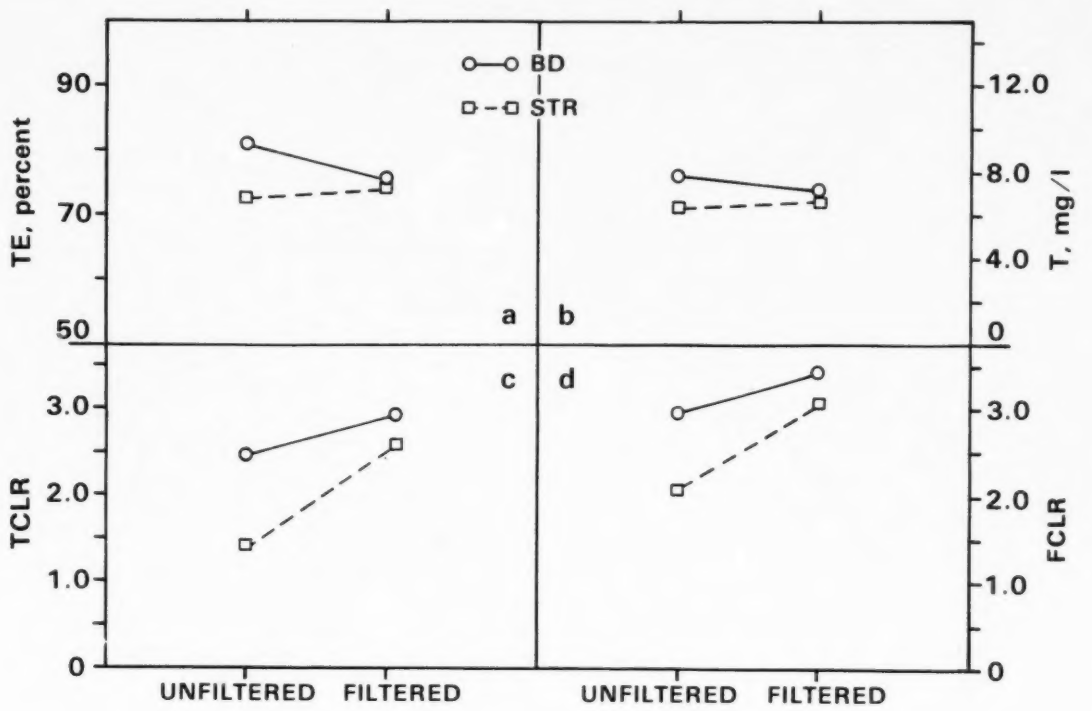

Fig. 6. Contactor × filter interaction (constant Y_1, varying Q_G/Q_L ratios).

been more sensitive to the effects of filtration than the stirred turbine reactor. With respect to microorganism reduction (Figs. 6c and 6d), no significant interactions occurred, indicating that the lines connecting the means in Figs. 6c and 6d are essentially parallel.

The filter main effect was derived by averaging together the data from both contactors and comparing the means for filtered and unfiltered effluent. The results were not significant with respect to TE and absorbed dose (Table 4) but significant at the 0.05 level with respect to coliform reduction. Although the latter results are not unequivocal, there is sufficient evidence to indicate that better disinfection will result if the effluent is filtered prior to ozonation.

The contactor main effect was derived by averaging together the data from filtered and unfiltered effluent and comparing the means for two contactors. The differences were highly significant with respect to mass transfer (Table 4) (i.e., more ozone was transferred to the liquid in the BD than in the STR). The overall mean transfer efficiency in the BD was 79% (7.5 mg/l) as against 73% (6.5 mg/l) in the STR. For TCLR and FCLR, the differences were significant, but only at the 0.05 level (the coliform measurement data were much more variable than the ozone measurement data). The overall mean TCLR and FCLR in the BD were 2.70 and 3.20, respectively, compared with 2.00 and 2.70, respectively, in the STR.

In summary, it is evident from examining Figs. 4 and 5 that the most significant differences occurred at the higher dose levels. Averaging together the results from all dose levels had the effect of dampening the overall differences observed between contactors and between filtered and unfiltered effluent (Fig. 6). If one were considering the whole plot analysis alone, one would conclude falsely that the differences observed between the BD and STR, or between filtered and unfiltered effluent, were not substantial enough to warrant a choice of one over the other. It was concluded that less efficient mass transfer but higher coliform reductions were achieved in filtered effluent. More efficient mass transfer and higher coliform reductions were achieved in the bubble diffuser. Thus, the increased surface area due to the violent shearing action in the turbine was insufficient to bring about a greater mass transfer rate than in the bubble diffuser.

Effect of increasing Y_1 at a constant Q_G/Q_L.

The objective of the second experiment was to evaluate the effect of increasing dose by increasing Y_1 while maintaining a constant Q_G/Q_L ratio. The Q_G/Q_L ratio chosen was 0.5 and the Y_1 values were 6, 12, and 18 mg/l. The conditions resulted in applied dose levels of 3, 6, and 9 mg/l, respectively.

Effluent Quality. Secondary effluent was obtained from the Fairfield Wastewater Treatment Plant (FWTP).

Table 5. Secondary effluent characteristics prior to ozonation (3/17/79 to 4/18/79).

Parameter	Unfiltered mean (range)	Filtered mean (range)
TCOD, mg/l	75 (25–146)	33 (22–52)
SCOD, mg/l	38 (18–60)	28 (18–46)
TOC, mg/l	13.9 (6.8–26.0)	8.3 (4.7–11.8)
TSS, mg/l	48 (6–96)	8 (1–17)
TKN, mg/l	17.7 (9.3–28.7)	12.9 (6.7–21.3)
NH_4^+–N, mg/l	12.5 (7.0–21.8)	11.1 (6.0–15.3)
NO_2^-–N, mg/l	1.0 (0.2–3.3)	0.2 (0.1–0.9)
NO_3^-–N, mg/l	0.5 (<0.1–1.6)	0.2 (<0.1–1.5)
Turbidity, JTU	10.2 (1.2–31)	2.0 (0.1–11)
Mn, mg/l	0.20 (0.09–0.66)	0.11 (0.01–0.37)
Fe, mg/l	0.27 (0.05–0.70)	0.11 (0.01–0.54)
pH	(5.8–6.9)	(6.1–7.4)
Temperature, °C	14 (12–17)	14 (12–17)
$\log_{10}$TC/100 ml	6.50 (5.45–7.01)	6.17 (5.63–6.55)
$\log_{10}$FC/100 ml	5.67 (5.07–6.12)	5.51 (5.11–5.86)

Table 5 summarizes the physical–chemical and bacteriological characteristics of the effluent before and after filtration and before ozonation. The unfiltered effluent was considerably lower in quality than the effluents used in the first experiment. Filtration removed 56% of the TCOD, and 84% of the TSS. Only modest removal of coliforms occurred as a result of filtration. The range in coliform numbers was typical of the expected range in secondary effluent.

Anova's. Table 6 summarizes the analyses of variance of all data from the second experiment with respect to each of the four dependent variables. As before, the significant interactions will be discussed first, and then the main effects.

A highly significant three-way interaction (dose × contactor × filter) occurred with respect to ozone transfer efficiency and absorbed dose. A graphical presentation of this effect is given in Fig. 7. If there had been no significant three-way interaction, the four curves in Figs. 7a and 7b would have been parallel, indicating consistent downward trends in TE and consistent upward trends in T with increasing dose. However, it is clear that the curve defining ozone transfer in the STR on filtered effluent had a steeper slope than the other three curves. This indicates that filtration had an increasingly marked effect on the transfer efficiency of the STR as dose increased. In other words, the STR was more sensitive to changes in effluent quality than the bubble diffuser, especially at higher doses. These changes in ozone transfer with dose were not large enough to cause a corresponding three-way interaction with respect to coliform reduction (Table 6).

The dose × contactor interaction was highly significant only with respect to transfer efficiency (Table 6). This is presented graphically in Fig. 8. The slopes of the curves in Fig. 8a are clearly convergent, whereas those in Figs. 8b, 8c, and 8d are essentially parallel. The explanation for the convergence in Fig. 8a becomes evident by reexamining Fig. 7a. Here, a sharp drop in TE occurred in the STR on filtered effluent as dose increased. Thus, when the data for both contactors were averaged together and compared, an interaction occurred due to the different slopes. However, this effect

Table 6. ANOVA for all data from second experiment (constant Q_G/Q_f, varying Y_1).

Source of variation	Degrees of freedom	Transfer Efficiency Mean square	Transfer Efficiency F	Absorbed Dose Mean square	Absorbed Dose F	TCLR Mean square	TCLR F	FCLR Mean square	FCLR F
Whole plot analysis									
Blocks (days) (B)	11	79.71	6.53**	0.36	8.09**	2.04	2.93	2.62	8.56**
Contactors (C)	1	245.68	20.14**	0.72	16.09**	0.027	0.04	0.46	1.51
Filter (F)	1	132.25	10.84**	0.67	14.90**	16.74	24.00**	15.64	51.03**
$C \times F$	1	40.11	3.29	0.27	5.96*	0.10	0.14	0.0040	0.01
Error a	9	12.20		0.045		0.70		0.31	
Split plot analysis									
Dose (D)	2	512.85	135.98**	126.06	2030.84**	29.90	56.89**	30.88	52.39**
$D \times C$	2	37.52	16.24**	0.035	2.16	0.68	2.51	0.080	0.44
$D \times F$	2	40.26	17.43**	0.55	34.12**	1.23	4.61*	0.86	4.75*
$D \times C \times F$	2	33.10	14.33**	0.24	14.78**	0.39	1.46	0.071	0.39
$B \times D$	22	3.77	1.63	0.062	3.82**	0.53	1.98	0.59	3.25
$D \times$ error a	18	2.31		0.016		0.27		0.18	
Total	71								

*Signfiicant at the $p < 0.05$ level.

**Significant at the $p < 0.01$ level.

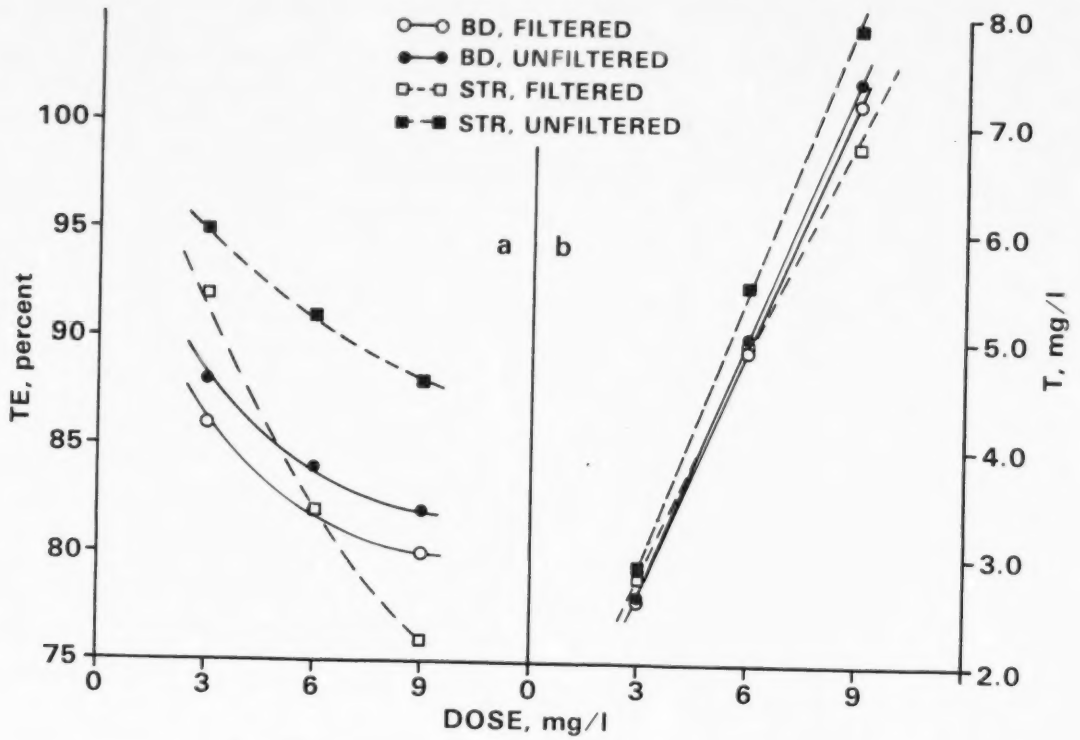

Fig. 7. Dose×contactor×filter interaction (constant Q_G/Q_l, varying Y_1).

was not large enough to cause substantial differences in contactors in either mass transfer *per se* or coliform reductions.

The dose×filter interaction was significant for all four dependent variables (Table 6). Figure 9 demonstrates this clearly. The pairs of curves in Figs. 9a and 9b are convergent, indicating different reaction rates for filtered and unfiltered effluent.

Regarding the main effects, the following observations were made. The effect of effluent filtration was highly significant for all dependent variables. Examination of Fig. 9 reveals that, even though transfer efficiency and mass transfer *per se* were decreased after filtration, the effect on coliform reduction was marked. The overall average TE and T before filtration were 87% and 5.2 mg/l, respectively. After filtration, the averages were 84% and 4.9 mg/l. The overall average TCLR and FCLR before filtration were 2.20 and 2.29, respectively. After filtration, the averages were 3.56 and 3.61, respectively. This again points out the improvement in ozone disinfection efficiency when secondary effluent is filtered prior to ozone application.

The contactor main effect was significant only with respect to ozone transfer, not coliform reduction. The overall mean TE and T in the bubble diffuser were 84% and 5.0 mg/l. Although these were statistically significant, the differences for all practical purposes are considered negligible.

Regression analysis

Considerable variation in effluent quality prior to ozonation occurred in both experiments. This caused relatively high mean square errors in the TCLR and FCLR data. Referring back to the whole plot analysis portion of Table 4 for TCLR and FCLR, the error-*a* mean squares, which were actually the day×contactor interactions, were 0.93 and 0.58, respectively. The standard deviation of the difference between means can be calculated as follows:

$$\text{Standard deviation of difference} = [2(\text{error-}a \text{ mean square})/n]^{0.5}, \quad (4)$$

where n = number of observations creating the mean. In the split plot experiments discussed above, there were 12 observations creating the contactor means and 12 observations creating the means for filtered versus unfiltered effluent. Doubling the computed standard deviation from the above equation gives the approximate 95% confidence limits (CL) for detecting a significant difference between means. Thus, for TCLR,

$$95\%\ \text{CL} = 2(0.93/6)^{0.5} = 0.79.$$

A difference in TCLR of less than 0.79 log units was not detectable. For FCLR, the 95% CL for detecting a significant difference was 0.62.

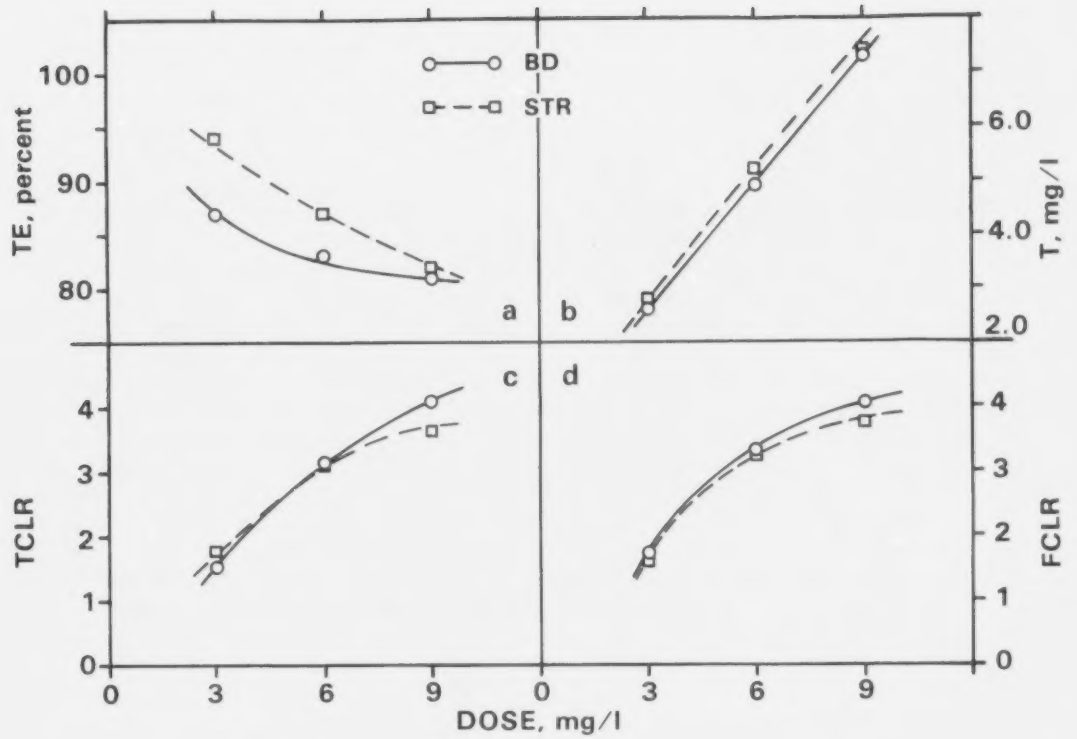

Fig. 8. Dose × contactor interaction (constant Q_G/Q_L, varying Y_1).

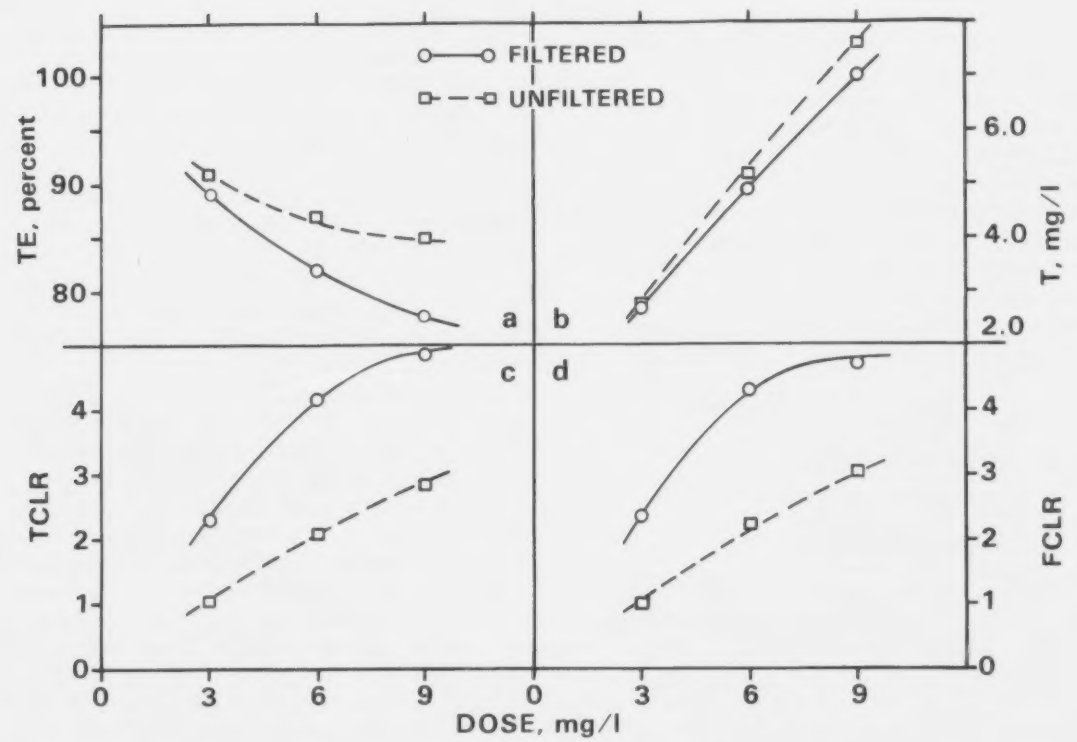

Fig. 9. Dose × filter interaction (constant Q_G/Q_L, varying Y_1).

An attempt was made to predict the final coliform levels as a function of the absorbed dose and the quality of the effluents prior to ozonation. This was done to help understand the high mean square errors in the coliform reduction data. Multiple regression analyses were performed. Effluent log total and fecal coliform numbers after ozonation were the dependent variables. The physical–chemical characteristics of the effluents prior to ozonation were the independent variables (i.e., TCOD, SCOD, TOC, TSS, turbidity, Fe, Mn, and nitrite). Additional independent variables included in the analyses were the ozone transfer data and ozone residual data.

It should be noted at this point that many of the independent variables were generally highly correlated. In effect this meant that several possible models could be developed using different independent variables. Since the independent variables were highly correlated, each model would do equally well in predicting log TC (total coliforms) and log FC (fecal coliforms). Thus, our goal here was not to decide which independent variables significantly affected the dependent variables. Rather, it was to try to develop models capable of predicting the dependent variables under different conditions. The only way to "test" whether each independent variable had a significant effect on the dependent variables would have been to formulate artificial wastewater in the laboratory so that the levels of each independent variable could be controlled to be orthogonal to one another.

For the regression, terms were kept in the model only if they were significant at the 5% level. In addition, a lack of fit test was done (Draper and Smith, 1966) in which simpler models were compared with the most complicated model possible (i.e., that which contained all independent variables). A model with fewer variables was kept only if the lack of fit from excluding a set of variables was nonsignificant. We report below the models we consider to be the best prediction equations. They were developed using the data set ($n=72$) from the second experiment described above (i.e., the one in which the applied dose levels were 3, 6, and 9 mg/l).

$$\log_{10}\text{TC} = 4.38 - 4.58\log_{10} T + 0.04\text{TCOD} \quad (5)$$

$$\log_{10}\text{FC} = 3.82 - 4.69\log_{10} T + 0.036\text{TCOD}, \quad (6)$$

where TC = total coliforms/100 ml

FC = fecal coliforms/100 ml

T = ozone transferred, mg/l.

The multiple correlation coefficients, r, for Eqs. (5) and (6) are 0.87 and 0.88, respectively. The resulting r^2 values are 0.76 and 0.77, respectively.

To test the ability of Eqs. (5) and (6) to predict final coliform numbers in ozonated effluent, data from the first experiment were used. The mean TCOD and ozone transfer were 38 mg/l and 6.4 mg/l, respectively. When Eqs. (5) and (6) were solved using the observed mean TCOD and $\log_{10} T$ data, the predicted $\log_{10}$TC and $\log_{10}$FC densities were 2.20 (or 158 TC/100 ml) and 1.40 (or 25 FC/100 ml), respectively. The corresponding observed $\log_{10}$TC and $\log_{10}$FC densities were 2.91 (or 813 TC/100 ml) and 1.89 (or 78 FC/100 ml), respectively. Although the predicted values underestimated the observed values, the differences were well within an order of magnitude.

Another test of the ability of Eqs. (5) and (6) to predict effluent coliform numbers after ozonation was made with a completely independent data set. The data used were from experiments conducted in 1978 comparing the disinfection efficiency of three different ozone contactors (Venosa *et al.*, 1979). The mean TCOD and ozone transfer levels were 35 and 5.2 mg/l, respectively. The $\log_{10}$TC and $\log_{10}$FC levels predicted by Eqs. (5) and (6) were 2.50 (or 316 TC/100 ml) and 1.72 (or 52 FC/100 ml), respectively. The corresponding observed mean coliform levels were 2.81 (or 650 TC/100 ml) and 1.92 (or 83 FC/100 ml). The agreement between observed and predicted values was excellent.

Summary and Conclusions

The analyses of variance of the data from the two experiments conducted in this study clearly indicated that filtration of secondary effluent prior to ozonation significantly improved the disinfection efficiency of ozone. However, since the total chemical oxygen demand played such an important role in influencing final coliform numbers in both experiments, it appears that the improved disinfection efficiency of ozone in filtered secondary effluent may have been due more to removal of the TCOD than to removal of the suspended solids. In fact, TSS was not found to be an important factor in influencing the final levels of coliforms in either of the ozonated effluents. This observation is similar to previous findings by Gan *et al.* (1977), who reported residual dissolved COD and nitrite had the greatest influence on disinfection with ozone, while suspended solids had little effect.

The models developed in this study [Eqs. (5) and (6)] were found to be reasonably good predictors of the final coliform densities after ozone disinfection. Although other models were possible, the models selected above were considered the most logical because (1) TCOD clearly exerts an ozone demand, (2) it is an easily measurable quantity, and (3) it was found to be orthogonal to (i.e., not autocorrelated with) ozone transfer.

It is concluded from this study that, for an average to poor quality secondary effluent, filtration may improve the likelihood of achieving a stated coliform objective, whereas for an above average effluent quality, filtration may not be necessary, as long as the TCOD levels are low enough.

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